Bioresource Technology 150 (2013) 476–485

Contents lists available at ScienceDirect

Bioresource Technology

journal homepage: www.elsevier.com/locate/biortech

Energy intensity, life-cycle greenhouse gas emissions, and economic assessment of liquid biofuel pipelines

Bret Strogen [a,*], Arpad Horvath [b], David Zilberman [a,c]

[a] Energy Biosciences Institute, 2151 Berkeley Way, Berkeley, CA 94704, USA
[b] Department of Civil and Environmental Engineering, 215 McLaughlin Hall, University of California, Berkeley, CA 94720, USA
[c] Department of Agricultural and Resource Economics, 207 Giannini Hall, University of California, Berkeley, CA 94720, USA

HIGHLIGHTS

- Energy use, GHG emissions, costs, and profits are modeled for biofuel pipelines.
- Design diameters are found that maximize NPV of ethanol and biodiesel pipelines.
- State-specific pipeline breakeven tariffs and GHG emission factors are presented.
- Pipeline performance is compared to alternative modes: trucks, trains, and barges.
- Pipeline competitiveness depends on location, flow rate, and economic conditions.

ARTICLE INFO

Article history:
Available online 3 September 2013

Keywords:
Freight transportation
Alternative fuel
Systems analysis
Climate policy, Life-cycle assessment

ABSTRACT

Petroleum fuels are predominantly transported domestically by pipelines, whereas biofuels are almost exclusively transported by rail, barge, and truck. As biofuel production increases, new pipelines may become economically attractive. Location-specific variables impacting pipeline viability include construction costs, availability and costs of alternative transportation modes, electricity prices and emissions (if priced), throughput, and subsurface temperature.

When transporting alcohol or diesel-like fuels, pipelines have a lower direct energy intensity than rail, barge, and trucks if fluid velocity is under 1 m/s for 4-inch diameter pipelines and 2 m/s for 8-inch or larger pipelines. Across multiple hypothetical state-specific scenarios, profit-maximizing design velocities range from 1.2 to 1.9 m/s. In costs and GHG emissions, optimized pipelines outperform trucks in each state and rail and barge in most states, if projected throughput exceeds four billion liters/year. If emissions are priced, optimum design diameters typically increase to reduce pumping energy demands, increasing the cost-effectiveness of pipeline projects.

1. Introduction

1.1. Biofuel policy goals and distribution challenges

Major goals motivating pro-biofuel policies in the United States stem from perceived supply chain benefits over petroleum, and include reducing life-cycle greenhouse gas emissions from the transportation sector, improving trade balance, diversifying energy supplies, reducing energy costs to consumers, and stimulating rural development by increasing demand for agricultural products (Rajagopal and Zilberman, 2007).The Energy Independence and Security Act of 2007 created the national goal to consume 36 billion gallons per year (bgy), i.e., 136 billion liters per year (bly), of biofuels by 2022 (Rahall [D-WV3], 2007). In 2011, the United States produced 14 billion gallons (49 billion L) of ethanol and only 970 million gallons (3.7 billion L) of biodiesel (US EIA, 2013a).

Due to the rural locations of many biorefineries, biofuels must be transported long distances to reach existing fuel blending infrastructure. Additionally, gasoline blends around the Midwest have become saturated at the E10 (gasoline containing 10% ethanol v/v) blend wall over the last decade. Under this constraint, Midwestern states have been increasing the quantity and distance of interstate ethanol shipments, and the average producer-to-consumer distance has exceeded 1100 km since 2004 (Strogen et al., 2012); this average distance is expected to increase by 2020 under most cellulosic ethanol scale-up scenarios considered by Scown et al. (2012), even if gasoline can be blended with up to 20% ethanol by volume. As the typical producer-to-consumer distance is unlikely to decrease over the next decade, transporting biofuels through pipelines is likely to be economically attractive under certain conditions.

---

* Corresponding author. Tel.: +1 (415) 483 2738.
E-mail addresses: bret@ce.berkeley.edu (B. Strogen), horvath@ce.berkeley.edu (A. Horvath), zilber11@berkeley.edu (D. Zilberman).

0960-8524/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.biortech.2013.08.150

In contrast to petroleum fuels and natural gas, which are distributed domestically by extensive pipeline networks (e.g., 283000 km of hazardous liquid pipelines), only 26 km of ethanol pipelines were registered with the Department of Transportation in 2011 (US DOT PHMSA, 2012). However, it is technically feasible and not uncommon to retrofit existing pipelines to handle new products (e.g., converting a gas line to a liquid fuel line), or to reverse the direction of flow in pipelines. Ethanol is already distributed occasionally through existing petroleum pipelines, though such conversion typically requires special precautions to ensure ethanol does not damage pipeline materials or degrade fuel quality (e.g., cleaning interior surfaces, upgrading materials, minimizing opportunities for fuel exposure to oxygen and water, and dosing fuel with corrosion inhibitors). Currently, there are few opportunities to utilize existing pipelines for biofuels, as the locations where most US biofuels are produced makes it "impossible to leverage the existing network" of petroleum infrastructure (US DOE, 2010). Even under optimistic scenarios with drop-in biofuel production increasing by 3 bly starting in 2015, new product pipelines would be required to transport biofuels from production facilities to the existing petroleum distribution system (NRC, 2013).

1.2. Economic and environmental aspects of pipelines

Current modes for transporting biofuels domestically (rail, truck, and barge) rely almost exclusively on petroleum-derived diesel or residual oil, and approximately half of petroleum products consumed in the United States are refined from imported crude oil (US EIA, 2013a). In contrast, liquid pipelines are predominantly powered by electricity, only 1% of which is generated from petroleum, as electricity is primarily generated from domestic non-petroleum resources (i.e., 42% coal, 24% natural gas, 19% nuclear, and 13% renewables in 2011 (US EIA, 2013a)). Therefore, shipping fuels by pipelines would reduce total supply chain demand for petroleum, and possibly total energy use and emissions. The relative performance superiority of one mode over another often changes under real world conditions, largely because energy intensity varies within each mode as a result of equipment technology and age, scale, geography, infrastructure quality and circuity, elevation change, congestion, operator behavior, and many other factors. Additionally, the GHG intensity of each mode depends on energy intensity of operations as well as the GHG intensity of the fuel source and supporting equipment and infrastructure.

The carbon content of petroleum fuels is a relatively consistent property, resulting in tailpipe emissions of 73–75 g CO_2-e/MJ for gasoline, diesel, and jet fuel (US DOE ANL, 2010), though tailpipe emissions typically only make up 81–85% of total fuel-cycle emissions (US DOE ANL, 2010; Dray et al., 2012). In contrast, state-average emissions per unit of generated electricity range from 1 gram CO_2-e per MJ of electricity (g CO_2-e/MJ_e) in Vermont (74% nuclear, 26% renewable) and 15 g CO_2-e/MJ_e in Idaho (80% hydro) up to 268 g CO_2-e/MJ_e in Wyoming (91% coal) and 314 g CO_2-e/MJ_e in Washington, DC (100% oil) (US EPA, 2012). As a result, if a pipeline is able to transport fluid at the identical energy intensity as a petroleum-powered vehicle, the resulting (operations only) emissions could be much less or much greater than vehicular transport.

2. Methods

2.1. Goal and scope

The economic and environmental aspects of transporting various liquid fuels by pipelines are estimated for comparison to alternative modes. A model was developed using a life-cycle framework to differentiate these impacts across various fuels and locations under plausible economic assumptions. As pipeline operating costs and emissions are tied to energy consumption, energy intensity values for pumping five different fuels are first estimated and presented for a range of pipeline design and operating configurations at the low and high temperature extremes (and therefore viscosity extremes) found in the contiguous United States.

Hypothetical pipelines are then designed, and life-cycle costs and GHG emissions estimated, for several volumetric flow rates, liquid fuels, and states. The boundary of analysis for pipelines includes initial construction, operations, and maintenance; alternative modes are assumed to already have infrastructure in place, so costs and emissions are modeled only for operations and maintenance activities. Results highlight the variability in conclusions that would be found when consideration is given to regional heterogeneity, specific fluid properties, and economies of scale in construction and operation.

2.2. Simplifying assumptions

In order to model the economic, energy, and environmental performance of a pipeline system, details must be understood about the fluid, pipeline dimensions, ambient conditions surrounding the pipeline, and the financial and resource inputs to constructing, operating, and maintaining a pipeline. For the purposes of developing a model with results that are easy to interpret and apply to specific case studies, the following simplifying assumptions and study limitations have been set.

1. The functional unit of service for evaluating freight transportation modes is the (metric) tonne-kilometer, t-km, (though transportation managers also value speed, reliability, and other considerations). Unlike pipelines, freight transport vehicles must return to their supplier; empty backhaul distance is assumed to be equivalent to delivery distance.
2. Transportation infrastructure circuity factors are ignored. That is, in comparing costs and emissions from transporting fuel 1000 km by pipeline to other modes, results are presented as if fuel would be transported 1000 km by alternative modes (though the actual distance along the best available route may be 800 or 1400 km, for example).
3. Fuel supply, fuel demand, and demand for transportation services are all assumed to be inelastic. That is, if pipelines perform better than other modes (e.g., at lower costs), there is no assumed change to the quantity, distance, or destination of fuels transported.
4. Although crude and product pipelines only operated at 73% and 57% of their design capacity in 1978 (Hooker, 1981), new biofuel pipelines are assumed to have a utilization rate (operations factor) of 90%, consistent with Pootakham and Kumar (2010). Therefore, the annual average flow rate is 90% of the flow rate found during actual operations. In reality, operation will not be as simple as "on/off" due to variations in fuel supply, fuel demand, and electricity prices. For example, operators may increase throughput during off-peak hours. As marginal electricity GHG emission factors may be 30% greater at night than at mid-day (Siler-Evans et al., 2012), such decisions may result in lower costs but greater energy and emissions intensity.
5. All fuels evaluated are assumed to be pure. In reality, fuels shipped through pipelines may contain small amounts of water, contaminants, or additives such as denaturants, drag reducing agents, corrosion inhibitors, biocides, among others. Costs and GHG emissions implications from such additives are ignored.
6. Insulation and heaters for pipelines were not considered in this analysis.